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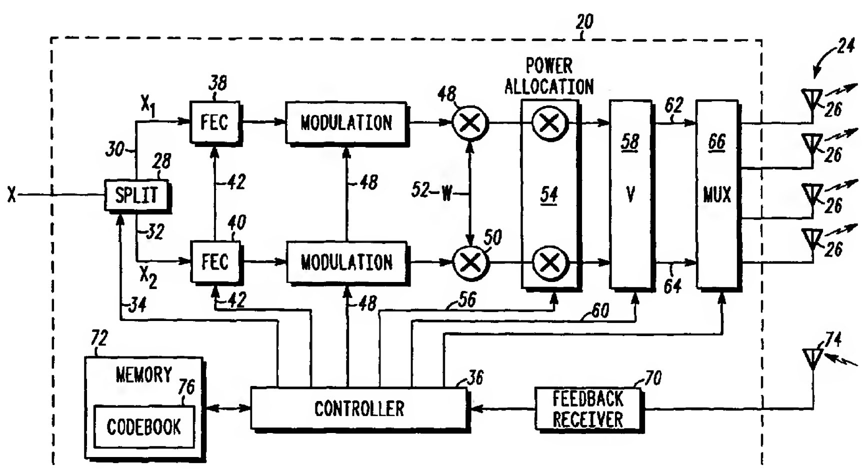
(54) **Title:** METHOD AND SYSTEM IN A TRANSCEIVER FOR CONTROLLING A MULTIPLE-INPUT, MULTIPLE-OUTPUT COMMUNICATIONS CHANNEL





(57) **Abstract:** The present invention makes it possible to increase a data rate between a transmitter and receiver using a multiple-input, multiple-output radio frequency channel. A multiple-stream, multiple-antenna receiver measures a composite channel between a multiple-antenna transmitter and a multiple-antenna receiver to produce a composite channel measurement. The receiver selects a plurality of antenna array weight sets for use in the multiple-antenna transmitter in response to the composite channel measurement, where each antenna array weight set is associated with one of multiple data streams. Information describing the plurality of antenna array weight sets for use in the multiple-antenna transmitter are then transmitted.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# METHOD AND SYSTEM IN A TRANSCEIVER FOR CONTROLLING A MULTIPLE-INPUT, MULTIPLE-OUTPUT COMMUNICATIONS CHANNEL

## Field of the Invention

The present invention is related in general to communication systems, and more particularly to a method and system for controlling the transmitting and receiving of multiple data streams in a multiple-input, multiple-output communications channel.

## Background of the Invention

Communication system designers are always looking for ways to increase the capacity of a communications channel between a transmitter and receiver. A communications channel may be defined as a system that transmits a sequence of symbols from one point to another. For example, a cellular communications system includes a channel for wirelessly transmitting a sequence of symbols that represent voice or data, back and forth between the telephone system and subscriber unit. An increase in the capacity of this channel means an increase in the rate of transmitting symbols. And when more symbols are transmitted in the same amount of time, voice can sound better, and it may take less time to transfer data files.

To increase the capacity of a wireless communications channel, antenna arrays have been used at the transmitter to better focus the transmitted energy at the receiver. An antenna array is a group of

spaced apart antennas that each transmit an antenna signal that has a specific gain and phase relationship with the other antenna signals. When the antennas work together transmitting the antenna signals, they produce an antenna pattern that is more focused on the receiver than a pattern produced by a single antenna. Note that the process of changing the gain and phase of a signal to produce antenna signals may be referred to as "weighting" the signal using a set of "antenna array weights."

Because antenna arrays may similarly be used at a receiver to improve signal quality, use of antenna arrays at both the transmitter and receiver has also been proposed to increase channel capacity. When multiple antennas are used at the transmitter and receiver, the wireless channel between them may be referred to as a multiple-input, multiple-output (MIMO) channel.

Fig. 1 shows a high-level schematic diagram of a communications channel, wherein a portion of the communications channel is wireless. As shown, x represents user data that will be wirelessly transmitted to the receiver. At the receiver, x is represented as an estimate of the data, $\hat{\mathbf{x}}$. User data x may be split to produce a vector that represents multiple data streams, $x_1$, $x_2$, ...

User data x is processed by matrix **V** to produce adaptive array antenna signals z. Each column of matrix **V** is a vector containing an antenna array weight set used to transmit one of the data streams $x_i$. Signals z are transmitted from antenna elements of the antenna array, through the air, and received at the receiver antenna array as received antenna signals r. The air interface between antenna signals z and received antenna signals r includes matrix H, which describes the effects of the air interface on signals z. The air interface is also described by the addition of noise n to signals z.

Received antenna signals r are processed in the receiver by matrix U' to produce the estimate of data, $\hat{\mathbf{x}}$.

With reference now to **Fig. 2**, there is depicted a two-input, two-output MIMO antenna array system. This MIMO system may be used to simultaneously transmit two different data streams, $x_1$ and $x_2$, to a single subscriber unit through a "composite channel" **H**, defined by the matrix

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

where $h_{ij}$ , $i = 1,2,$ $j = 1,2$ are complex channel values. Note that the term "composite channel" as used herein refers to a complete measurement or description of a channel, wherein the effects of all combinations of transmit antennas and receive antennas are considered. The composite channel may be thought of as the aggregation of all channels between pairs of single antennas, defined by all pair-wise combinations of transmit and receive antennas.

When a flat Rayleigh fading channel is assumed, $h_{ij}$ are complex-valued Gaussian numbers with unity average power, $E[h_{ij}h_{ij}^*] = 1$. The received (baseband) vector **r** (see **FIG. 1**) can be written as follows

$$\mathbf{r} = \mathbf{Hx} + \mathbf{n}$$

where $\mathbf{x} = [x_1 \quad x_2]^T$ is the vector of transmitted data streams, and **n** is a vector of noise samples, with additive white Gaussian noise with variance $\sigma_n^2$.

Note that in a noise free channel, both streams can be recovered perfectly if channel matrix **H** is full rank. That is, two equations and two unknowns can be solved to recover the unknowns $\mathbf{x} = [x_1 \quad x_2]^T$. When $\mathbf{x} = \mathbf{H}^{-1}\mathbf{r}$, both data streams can be recovered and link, or channel, capacity can be doubled. For example, a linear architecture may use zero forcing receivers to multiply the received vector **r,** with $\mathbf{H}^{-1}$. This works well with a high signal-to-noise ratio (SNR), but with a low SNR it boosts noise, which is not desirable.

In another linear receiver architecture, a Minimum Mean Square Error (MMSE) receiver may be used to minimize the average difference between detected data streams and the received signal.

While linear and non-linear receiver architectures can both be implemented to detect the multiple streams in noisy channels, in practical applications, noise in the channel will often require the use of non-linear receivers, which are more complicated and expensive to build. Examples of non-linear receivers with improved performance are Serial-Interference-Cancellation (SIC) receivers and a Maximum Likelihood (ML) receivers. Because of their complexity and cost, non-linear receivers should be avoided if possible.

**Theoretical MIMO Capacity:**

The capacity of a MIMO system may be shown with the following analysis. Suppose the Singular Value Decomposition (SVD) of the channel matrix **H** is given by

$$\mathbf{H} = \mathbf{U}\mathbf{S}\mathbf{V}' \tag{1}$$

where **S** is a diagonal matrix composed of the singular values (i.e., the square-roots of eigenvalues of $\mathbf{H}'\mathbf{H}$ or $\mathbf{H}\mathbf{H}'$), **U** is an orthogonal matrix

with column vectors equal to the eigenvectors of $\mathbf{HH}'$, $\mathbf{V}$ is an orthogonal matrix with columns equal to the eigenvectors of $\mathbf{H}'\mathbf{H}$, and the "$'$" operator is the complex conjugate transpose operation. As an example, consider the following composite channel matrix

$$\mathbf{H} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{1.1}$$

The SVD of this composite channel is

$$\mathbf{H} = \mathbf{USV}' = \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \begin{bmatrix} \sqrt{2} & 0 \\ 0 & \sqrt{2} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{1.2}$$

Referring to **Fig. 1**, the transmit vector is

$$\mathbf{z} = \mathbf{Vx} \tag{2}$$

Thus, the received vector is

$$\mathbf{r} = \mathbf{Hz} + \mathbf{n} \tag{3}$$

Replacing $\mathbf{H}$ and $\mathbf{z}$ with (1) and (2), we get

$$\mathbf{r} = \mathbf{USV}'\mathbf{Vx} + \mathbf{n} = \mathbf{USx} + \mathbf{n} \tag{4}$$

where, since $\mathbf{V}$ is an orthonormal matrix, $\mathbf{V}'\mathbf{V}$ is replaced with identity. Next, the received vector is pre-multiplied with $\mathbf{U}'$:

$$\begin{aligned} \hat{\mathbf{x}} &= \mathbf{U}'\mathbf{USx} + \mathbf{U}'\mathbf{n} \\ &= \mathbf{Sx} + \mathbf{e} \end{aligned} \tag{5}$$

Again, since $\mathbf{U}$ is an orthonormal matrix, $\mathbf{U}'\mathbf{U}$ is replaced with identity. Note that the new noise vector, $\mathbf{e}$, has the same covariance

matrix as $\mathbf{n}$, because pre-multiplication with an orthonormal matrix does not alter the noise covariance.

If equation (5) is rewritten for the case of 2 transmit antennas, and 2 receive antennas it becomes:

$$\begin{bmatrix} \hat{\mathbf{x}}_1 \\ \hat{\mathbf{x}}_2 \end{bmatrix} = \begin{bmatrix} \sqrt{\lambda_1} & 0 \\ 0 & \sqrt{\lambda_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} \sqrt{\lambda_1} x_1 + e_1 \\ \sqrt{\lambda_2} x_2 + e_2 \end{bmatrix} \tag{6}$$

where $\lambda_i$ are the channel matrix eigenvalues.

The error free channel capacity based on the Shannon bound is well known, and is given by

$$\mathrm{C}_1 = \log_2(1+\rho) \quad \text{bits/symbol} \tag{7}$$

where $\rho$ is the channel SNR. From (5) and (6), note that the MIMO channel capacity based on the Shannon bound is the sum of the capacities per data stream:

$$C_{\mathrm{MIMO}} = \sum_{i=1}^{M} C_i = \sum_{i=1}^{M} \log_2\left(1 + \frac{\rho}{M}\lambda_i\right) \quad \text{bits/symbol} \tag{8}$$

where M is the minimum number of antennas at either the transmitter or the receiver. For the 2 transmit antenna, 2 receive antenna example, M=2. It is important to note that in (8), the total transmit power has been normalized such that it remains the same for any number of transmit antennas. The ratio $\rho/M$ ensures equal power transmitted on all antennas, and it maintains the same total power for all values of M.

In general, equal power transmission of (8) is sub-optimal. The total capacity, which is the sum of each data stream capacity, $C_{\mathrm{MIMO}} = \sum_i C_i$, can be maximized by increasing the power to the high SNR streams, and reducing the power to the low SNR streams, such that the total transmit power remains the same. This procedure is typically referred to as "waterfilling."

By including waterfilling weights for optimum power allocation per data stream, (8) becomes:

$$C_{\mathrm{MIMO}} = \sum_{i=1}^{M} \log_2\left(1 + \frac{\rho}{M}\lambda_i w_i\right) \quad \text{bits/symbol} \tag{9}$$

where waterfilling weights are computed from

$$\sum_i w_i = \sum_i \max\left[0, \left(K - \frac{\sigma_n^2}{\lambda_i}\right)\right] = 1,$$

which is the waterfilling criterion, which is discussed by R.G. Gallager in *Information Theory and Reliable Communication,* New York: John Wiley & Sons, 1968. Here, $K$ is a constant determined by iterations, and $w_i$ are set accordingly.

Because transmitters in prior art systems lack data regarding the conditions of the composite channel, the performance of these systems cannot approach the Shannon bound for the MIMO channel. Furthermore, the amount of data needed to describe a composite MIMO channel is large, which would consume a large percentage of channel capacity when communicated to the transmitter.

Thus, it should be apparent that a need exists for an improved method and system for using feedback to efficiently control data

transmission and reception in a multiple-input, multiple-output radio frequency channel.

## Brief Description of the Drawings

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objects, and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

**FIG. 1** is a high-level schematic diagram of a communications channel, wherein a portion of the communications channel is wireless;

**FIG. 2** is a high-level block diagram of a two-input, two-output MIMO channel;

**FIG. 3** is a block diagram of a multiple-stream, multiple-antenna transmitter that may be used to implement the method and system of the present invention;

**FIG. 4** is a more detailed block diagram of antenna array signal processor;

**FIG. 5** depicts a receiver for use in a multiple-stream, multiple-antenna transceiver system in accordance with the method and system of the present invention;

**FIG. 6** is a high-level logic flowchart that illustrates a feedback method in a multiple-stream, multiple-antenna receiver in accordance with the method and system of the present invention;

**FIG. 7** is a high-level logic flow chart that illustrates a feedback method in a multiple-stream, multiple-antenna transmitter in accordance with the method and system of the present invention;

**FIG. 8** is a more detailed logical flow chart that illustrates the process for estimating a composite channel and selecting array weight sets in accordance with the method and system of the present invention;

**FIG. 9** shows simulation results comparing quantized MIMO feedback with un-quantized, ideal MIMO feedback, in accordance with the method and system of the present invention; and

**FIG. 10** shows simulation results for a MIMO transceiver system in accordance with the method and system of the present invention.

## Detailed Description of the Invention

With reference now to **FIG. 3**, there is depicted a multiple-stream, multiple-antenna transmitter that may be used to implement the method and system of the present invention. As illustrated, transmitter **20** receives user data **22** and transmits user data **22** using antenna array **24**, which comprises antenna elements **26**.

User data **22** enters data splitter **28**, which separates the user data stream into a plurality of data streams, such as data stream **30** and data stream **32**. While two data streams are shown in **FIG. 3**, data splitter **28** may produce any number of data streams. Data splitter **28** splits data in proportion to control signal **34**, which is produced by controller **36**. For example, control signal **34** may specify a ratio of 2-to-1, wherein two bits are sent to data stream **30** and one bit is sent to data stream **32**. This splitting ratio may specify an equal number of bits on both streams, or all data bits are sent to one stream.

Data streams **30** and **32** output by data splitter **28** are input into error correction encoders **38** and **40**. These error correction encoders may be implemented with a convolutional encoder, a turbo encoder, a block encoder, or the like. The type of encoding, and the rate of encoding is controlled by control signal **42**, which is output by controller **36**. Note that control signal **42** may set error correction encoders **38** and **40** to the same error encoding schemes, or different encoding schemes.

Outputs of error correction encoders **38** and **40** are coupled to inputs of modulators **44** and **46**. Modulators **44** and **46** may be implemented with linear or non-linear modulation schemes, including

all varieties of modulators that modulate amplitude and phase, and combinations of amplitude and phase. Examples of modulators that may be used include Binary Phase Shift Keying modulators (BPSK), Quadrature Phase Shift Keying modulators (QPSK), M-ary phase shift keying modulators, M-ary quadrature amplitude modulators (MQAM), and the like.

Control signal **48** selects the type of modulation used in modulators **44** and **46**. Control signal **48** is produced by controller **36**. According to the present invention, the modulation schemes in the data streams may be the same, or different.

The output of modulators **44** and **46** are coupled to inputs of spreaders **48** and **50**, respectively. Spreaders **48** and **50** spread the signal using spreading code **52**, wherein the spreading code is assigned to user data **22**.

Outputs of spreaders **48** and **50** are coupled to inputs of power allocator **54**. Power allocator **54** sets a power ratio between data streams **30** and **32** in response to control signal **56** from controller **36**. Power allocator **54** may allocate all power to one data stream, equal powers on data streams, or other ratios of unequal power allocations.. Power allocator **54** does not allocate power to data streams **30** and **32** relative to data streams belonging to other user data not shown in **FIG. 3**. This means that power allocator **54** does not allocate an absolute level of power to a user. The absolute power allocated to each data stream, and each user, is determined by available power in power amplifiers and other control functions not shown in **FIG. 3**.

Outputs of power allocator **54** are coupled to inputs of antenna array signal processor **58**, which further processes the data streams

by applying antenna array weight sets to each data stream. These antenna array weight sets come from controller **36** via control signal **60**. By applying the antenna array weight sets to data streams **30** and **32**, antenna array signal processor enables the transmission of each data stream with a different antenna array pattern.

The outputs of antenna array signal processor **58** include weighted components of the input data streams. For example, output **62** may include a phase-and-gain weighted portion of data stream **30** added together with a phase-and-gain weighted portion of data stream **32**. The number of weighted outputs from antenna array signal processor **58** may be equal to or greater than the number of data streams. While the number of outputs of antenna array signal processor **58** may be greater than the number of data streams input, the number of data streams transmitted remains the same.

With reference now to **FIG. 4**, there is depicted a high-level block diagram of antenna array signal processor **58**. As shown, data streams **30** and **32** enter antenna array signal processor **58**, wherein a copy of each data stream is sent to a gain multiplier corresponding to an antenna element that will be used in an antenna array. In the example shown in **FIG. 4**, two antennas will be used in the antenna array, therefore copies of each data stream are sent to two gain multipliers **80**.

Following each gain multiplier **80** is a phase shifter **82**, which rotates the phase of the signal according to a control signal input. Outputs of phase shifters **82** are coupled to summers **84**, which add the weighted data streams to produce output signals **62** and **64**.

Control signal **60** (see **FIG. 3**) includes a plurality of antenna array weight sets, wherein one antenna array weight set is associated

with each data stream. For example, control signal **60** includes weight set signals **86** and **88**. Weight set signal **86** includes gain and phase weights (i.e., complex weights) for each gain multiplier **80** and phase shifter **82** associated with data stream **30**. Thus, the outputs of phase shifters **82** associated with data stream **30** produce antenna signals that provide a selected antenna pattern for data stream **30**. Similarly, weight set signal **88** includes phase and gain weights for each gain multiplier **80** and phase shifter **82** associated with data stream **32**. In the outputs of phase shifters **82** associated with data stream **32** produce antenna signals for driving an antenna array with a selected pattern for data stream **32**.

In order to produce desired antenna patterns for each data stream, gain multipliers **80** associated with a data stream may have different gain values and phase shifters **82** associated with a data stream may have different phase shift values, whereby producing antenna signals that work together to form a particular transmission pattern.

In some embodiments of transmitter **20**, output signals **62** and **64** may be up-converted, amplified, and coupled to two antenna elements **26**. However, in the embodiment shown in **FIG. 3**, multiplexer **66** is used to couple output signals **62** and **64** to selected antenna elements **26** in response to control signal **68** from controller **36**. This means that control signal **62** may be coupled to any one of antenna elements **26** in antenna array **24**, while output signal **64** is coupled to one of the remaining antenna elements **26**.

Controller **36** outputs control signals **34**, **42**, **48**, **56**, **60**, and **68** based upon information received from feedback receiver **70**, and data stored in memory **72**. Feedback receiver **70** is shown coupled to antenna **74** for receiving feedback data from a remote receiver, such

as the receiver shown in **FIG. 5**. While antenna **74** is shown separate from antenna array **24**, one of the antenna elements **26** of array **24** may be used to receive the feedback data.

Feedback data from feedback receiver **70** may include a codebook index, which may be used by controller **36** to lookup transmission parameters in codebook **76** within memory **72**.

Controller **36** may also be used to calculate, or derive, additional control signals or transmission parameters based upon feedback data. Therefore, it should be understood that feedback data may include measurements upon which calculations may be based, or data that indicates parameters to be used in transmitter **20**.

With reference now to **FIG. 5**, there is depicted a receiver for use in a multiple-stream, multiple-antenna transceiver system in accordance with the method and system of the present invention. As shown, receiver **98** includes antenna array **100** having elements **102** that receive radio frequency signals **104** and **106**. Received RF signals **104** and **106** are most likely different signals because antenna elements **102** are spaced apart, and propagation paths taken by received RF signals **104** and **106** from antenna elements **26** of transmitter **20** are most likely different in a multi-path fading environment.

In the multiple-stream, multiple-antenna transceiver system that is made up of transmitter **20** and receiver **98**, multiple data streams are transmitted to increase the data throughput between transmitter **20** and receiver **98**. Transmitter **20** is able to simultaneously transmit multiple data streams, and receiver **98** is able to keep the multiple streams separate by exploiting the differences in the channel characteristics between the multiple

antennas at transmitter **20** and receiver **98**. Thus, user data **22** in transmitter **20** is received by receiver **98** and output as estimated user data **108**.

Received RF signals **104** and **106** are input into radio frequency receiver front end **110**, wherein the radio frequency signals are down converted and digitized. The output of radio frequency receiver front end **110** is a stream of complex baseband digital samples that represent received RF signals **104** and **106**.

The outputs of radio frequency receiver front end **110** are input into receiver signal processor **112**, which has the function of separating data streams **30** and **32** (See **FIG. 3**) in receiver **98**. In one embodiment of the present invention, receiver signal processor **112** may be implemented by multiplying the input signals by the complex conjugate transpose of the **U** matrix, which is the left singular vectors of the singular value decomposition of the composite channel matrix **H**. Receiver signal processor **112** is controlled by control signal **115** from controller **113**.

The data streams output by receiver signal processor **112** are input to despreaders **114** and **116**, which despread the signals using spreading code **52**, which is the same spreading code used in the transmitter. The outputs of despreader **114** and **116** are coupled, respectively, to the inputs of demodulator and decoders **118** and **120**. Each demodulator and decoder **118** and **120** demodulates the signal and decodes the signal using demodulation and error correction decoding techniques that compliment those selected for each data stream in the transmitter. Thus, the type of demodulator and decoder functions used depends upon what was used in transmitter **20**, as indicated by control signal **122** from controller **113**. Demodulators

and decoders **118** and **120** may be the same function, or may be different functions.

The outputs from demodulator and decoder **118** and **120** are input into combiner **124**, which combines the multiple streams received back into a single stream for output as estimated user data **108**. Combiner **124** operates under the control of controller **113**, as directed by control signal **126**. Because the received data streams may have different data rates, and because one data stream may have a data rate equal to zero, combiner **124** must reconstruct the user data in accordance with the way data was originally split by data splitter **28** in transmitter **20** in **FIG. 3**.

In order to control the transmission of multiple data streams via multiple antennas at the transmitter, receiver **98** must measure the composite channel and send feedback data to the transmitter. As shown, outputs of radio frequency front end **110** are also coupled to composite channel estimator **128**, which uses pilot signals transmitted from each antenna element **26** in transmitter **20** to measure the composite channel between the multiple input antennas and multiple output antennas. The function of composite channel estimator **128**, and many of the other functional blocks in the data feedback portion of receiver **98**, are described in more completely in reference to **FIG. 8**, below.

The output of composite channel estimator **128**, which is represented by the **H** matrix, is input into **V** matrix computer and selector **130**. The "computing function" of block **130** computes **V**, which is a matrix describing desired antenna array weight sets to be used for each data stream in transmitter **20**. The desired antenna array weight sets are computed based upon the composite channel measurement.

The "selector function" of block **130** is a quantizing function that selects antenna array weight sets that most closely match the desire antenna array weight sets. By performing quantization, the amount of feedback data required to instruct transmitter **20** how to transmit over the MIMO channel may be reduced.

The selected antenna array weight sets output by computer and selector **130** are input into SNR computer and power allocator **132**, wherein a signal to noise ratio is computed for each data stream hypothetically transmitted using the selected antenna array weight sets. Based upon the SNR computations, the power allocation function of block **132** allocates power to each data stream, wherein the power is allocated to maximize the data throughput based upon a waterfilling algorithm. Once power has been allocated to each data stream, final SNR calculations may be performed using the selected power allocation.

Modulator and coder **134** receives information from SNR computer and power allocator **132** that it uses to select an encoding scheme and a modulation scheme to be used in transmitter **20**. Generally, higher order modulators are selected for data streams having high signal-to-noise ratios.

Feedback transmitter **136** receives information from the **V** matrix computer and selector **130**, SNR computer and power allocator **132**, and modulator and coder selector **134**. This data represents calculations and selections made in receiver **98** that will be used to control the transmission modes of transmitter **20**. In a preferred embodiment, feedback transmitter **136** analyzes the data and selects a codebook value associated transmitter parameters that most closely match the transmitter parameters represented by the input data. Therefore, feedback transmitter **136** may include codebook **138** for

producing a codebook value that is transmitted to transmitter **20** via antenna **140**. Although antenna **140** is shown separate from receive antenna array **100**, antenna **140** may be one of the antenna elements **102** in receive antenna array **100**. Data transmitted by feedback transmitter **136** is received in transmitter **20** by feedback receiver **70**.

With reference now to **FIG. 6**, there is depicted a high-level logic flowchart that illustrates a feedback method in a multiple-stream, multiple-antenna receiver in accordance with the method and system of the present invention. As illustrated, the process begins at block **300**, and thereafter passes to block **302** wherein the composite channel between the multiple-antenna transmitter and the multiple-antenna receiver is measured. This measurement results in the formation of the **H** matrix that is made up of complex channel values, representing gains and phases, as discussed above in reference to **FIG. 2**. The composite channel measurement is made by analyzing received antenna signals **r** (See **FIG. 1**) that include received pilot signals transmitted by each antenna at the transmitter.

Next, the process selects an antenna array weight set associated with each data stream in response to the composite channel measurement, as depicted at block **304**. Note that each simultaneously transmitted data stream has an associated set of weights that are used for each array antenna at the transmitter. Each antenna array weight set is used to produce an antenna pattern for the associated data stream.

In a preferred embodiment, selected antenna array weight sets are determined by calculating the right singular vectors of the SVD of composite channel matrix **H**. This process is more completely described with reference to **FIG. 8**. To reduce the amount of data needed to represent the antenna array weight sets, the desired weight

sets are compared to weight sets in a codebook, and one or more codebook weight sets having the closest distance are selected. The codebook indicator may represent a single antenna array weight set, or a combination of antenna array weight sets.

Note that if predefined combinations of antenna array weight sets are used, a first amount of information may be transmitted to describe a first antenna array weight set, and a second amount of information may be transmitted to describe a second antenna array weight set, wherein the second amount of information may be less than the first amount of information. Similarly, if a second antenna array weight set is restricted, or constrained, to a have a predefined relationship to a first antenna array weight set, the amount of information needed to describe the second set is less than that needed to describe the first.

Once selected, the antenna array weight sets are transmitted to the transmitter, and the transmitter uses the weights to produce selected antenna patterns for each data stream, as illustrated at block **306**. Because of the volume of data that may be needed to represent a complex weight for each antenna, for each data stream, it may be advantageous to use techniques that reduce the number of data bits transmitted from the receiver to the transmitter. As mentioned above, a codebook may be used to store several predefined antenna array weight sets. The number of antenna array weight sets available will determine the resolution of the quantizing process that takes an ideal set of weight sets and maps it to one of the available antenna array weight sets. Note that quantizing errors may become excessive if the number of available antenna array weight sets is too small.

As mentioned above, another way to reduce the amount of feedback data is to constrain the transmitter to transmitting antenna

patterns that have selected relationships with one another. For example, in a preferred embodiment, the antenna patterns at the transmitter may be constrained to be orthogonal to one another. Thus, by specifying a first antenna pattern, any remaining patterns at the base may be calculated, at least partially, according to the constraint relationships. Therefore, in a transmitter that transmits two data streams, if a first antenna pattern is specified, the antenna pattern for the second data stream may be derived, or calculated, so that the second pattern is constrained to be orthogonal to (or have low correlation with) the first.

**Details on V Quantization**

The simplest method of quantizing a matrix is to quantize each element of the matrix individually. Unfortunately, this method is inefficient and will require the greatest number of feedback bits for a desired performance. V may be quantized with two basic approaches: "block" and "incremental" quantization. In the first approach, all columns of V are quantized at once. In the second approach, columns of V are quantized incrementally.

**Block V Quantization**

Because the **V** matrix is orthonormal, it has some structure that can be exploited to reduce the amount of feedback. For the 2-antenna transmitter and 2-antenna receiver case, the **V** matrix can be written as

$$\mathbf{V} = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ e^{j\theta} \cdot \sin\alpha & -e^{j\theta} \cdot \cos\alpha \end{bmatrix},$$

where

$$\alpha = \cos^{-1}(v_{11}),$$
$$\theta = \angle v_{21}.$$

The entire **V** matrix can be represented by two real parameters. Using this representation, there is a sign ambiguity in the second column vector that must be handled at the receiver. Fortunately, the transmission remains orthogonal and an MMSE receiver handles the sign ambiguity automatically. The parameters $\alpha \in \left[0, \frac{\pi}{2}\right]$ and $\theta \in [0, 2\pi]$ are uniformly quantized to a desired level. Figure 5 shows that quantizing **V** with 5 bits (3 for $\boldsymbol{\theta}$, 2 for $\boldsymbol{\alpha}$) and using an MMSE receiver is within 0.4 dB of the unquantized case.

In general, a codebook of **V** matrices can be created and indexed. A technique such as vector quantization can be used to generate the codebook and also to create an efficient mapping between **V** and the codebook. Parametric quantization as used in the 2x2 case can also be extended to larger **V** matrices.

**Incremental V Quantization**

In this approach, the columns of V are repeatedly drawn from a codebook of antenna array weights. (For example, one may use the TX AA codebooks from the 3GPP standard, release 99, or extensions of these codebooks.) The correlation properties of the columns of V are mirrored by selecting successive antenna array weight sets from increasingly smaller subsets of the codebook. As will be shown below, this constrained search reduces the amount of feedback data.

The column of V corresponding to the highest quality stream is selected first. This column is selected as the antenna array weight set that produces the maximum power at the receiver. The entire codebook is searched for this weight set.

Next, a second column of V is selected. A subset of the antenna array codebook may be found by searching for a codebook entries that have a correlation below a desired correlation threshold. The correlation threshold may be set to zero to select an orthogonal subset. Then, the antenna array weight set that produces maximum power at the receiver is selected from the low correlation subset of the codebook.

If there are three data streams, the third column of **V** is selected from a subset of the subset of codebook entries that was searched for the second column of **V**. The subset contains antenna array weight sets with low correlation against the subset searched for the second column. This process continues for all streams.

Since successive columns of **V** are searched from successively smaller subsets of the antenna array codebook, successive columns of **V** can be represented with fewer feedback bits. In a 4-element antenna array codebook with 64 entries, the antenna array weight set for the first column of **V** can be represented with log2(64) = 6 bits. By selecting an appropriate correlation threshold, the second column of **V**'s weight set can be represented with 4 bits, a third column with 2 bits, and the fourth column with 0 bits (only 1 antenna array weight set is possible, given the correlation constraint and the choice of the other 3 antenna array weight sets.) Therefore, the entire **V** matrix can be quantized with 12 bits.

The size of codebook subsets may not be integer powers of two (since their size is determined by the correlation threshold), which means that the successively computed weight sets are not efficiently quantized using an integer number of bits to separately represent each weight set. In this case, alternate embodiments may jointly code the weight sets using vector quantization, or use variable length code words to reduce the number of bits required to represent the entire **V** matrix. Note that these alternate embodiments still draw the antenna array weight sets from subsets of a single codebook of antenna array weight sets, with the difference being the source coding used to reduce the number of bits required to represent the **V** matrix.

In addition to feeding back selected antenna array weight sets, the receiver may also feedback data that allows the transmitter to select a forward error correction coding scheme, a modulation scheme, a power allocation for each data stream, and a selection of antennas in the transmit antenna array.

As shown in block **308,** the process may select a data rate for each data stream in response to the composite channel measurement, the selected antenna array weight set, and SNR for each data stream. In a preferred embodiment, the SNR for each data stream is used to lookup a combination of encoding and modulation techniques according to calculated performance curves, and assuming equal power is available for both data stream. This lookup will provide an aggregated data throughput. This throughput value is compared to a second lookup assuming that all the power is used in the data stream having the highest signal to noise ratio. The second lookup gives a second data throughput, and the encoding and modulation scheme at the particular power setting is selected based upon the maximum throughput.

In a preferred embodiment, the codebook shown in table 1 below may be used in a system that sends four bits of feedback from the receiver to the transmitter in order to specify modulation and error encoding schemes for each data stream, and power allocation for each data stream. Note that antenna array weight sets are not included in the codebook of table 1.

| Configuration # | Modulator #1 | Code #1 | Modulator #2 | Code #2 | Power 1 | Power 2 |
|---|---|---|---|---|---|---|
| 1 | QPSK | R=1/2 | ---- | R=1/2 | 1 | 0 |
| 2 | QSPK | R=1/2 | QPSK | R=1/2 | 0.5 | 0.5 |
| 3 | 16 QAM | R=1/2 | ---- | R=1/2 | 1 | 0 |
| 4 | 16 QAM | R=1/2 | QPSK | R=1/2 | 0.5 | 0.5 |
| 5 | 16 QAM | R=1/2 | 16 QAM | R=1/2 | 0.5 | 0.5 |
| 6 | 64 QAM | R=1/2 | ---- | R=1/2 | 1 | 0 |
| 7 | 64 QAM | R=1/2 | QPSK | R=1/2 | 0.5 | 0.5 |
| 8 | 64 QAM | R=1/2 | 16 QAM | R=1/2 | 0.5 | 0.5 |
| 9 | 64 QAM | R=1/2 | 64 QAM | R=1/2 | 0.5 | 0.5 |
| 10 | 256 QAM | R=1/2 | ---- | R=1/2 | 1 | 0 |
| 11 | 256 QAM | R=1/2 | QPSK | R=1/2 | 0.5 | 0.5 |
| 12 | 256 QAM | R=1/2 | 16 QAM | R=1/2 | 0.5 | 0.5 |
| 13 | 256 QAM | R=1/2 | 64 QAM | R=1/2 | 0.5 | 0.5 |
| 14 | 256 QAM | R=1/2 | 256 QAM | R=1/2 | 0.5 | 0.5 |

**Table 1**

After the data rate is selected, the process transmits the selected data rate to the transmitter so the transmitter can select data encoding and modulation schemes for each data stream, as illustrated at block **310**. In a preferred embodiment of the invention, the receiver computes data rates, encoding schemes, modulation schemes, and power levels for each data stream, and transmits data that indicates these selections to the transmitter. In an alternative embodiment, the receiver may transmit measurements, or data based upon measurements, to the transmitter so that the transmitter may select a data rate, an encoding scheme, a modulation scheme, and a power allocation for each data stream.

Once the feedback data is transmitted from the receiver to the transmitter, the process ends, as depicted at block **312**. Although an end to the receiver feedback process is shown at block **312**, the process may iteratively continue in the receiver, beginning again at block **302** with new composite channel measurements.

With reference now to **FIG. 7**, there is depicted a high-level logic flow chart that illustrates a feedback method in a multiple-stream, multiple-antenna transmitter in accordance with the method and system of the present invention. As illustrated, the process begins at block **400**, and thereafter passes to block **402** wherein the process transmits a pilot signal on each antenna of the antenna array. Each pilot signal is distinguishable from the others. For example, different spreading codes may be used, or the same spreading code may be shifted in time relative to the other array antennas. These pilot signals provide a reference signal for the composite channel measurement.

Next, the process receives indications of a selected array weight set, with one set per data stream, as illustrated at block **404**. The indications of selected array weight sets may be data that describe a set of gains and phases for antenna signals for each antenna, with a set for each data stream in the transmitter. In a preferred embodiment, the selected array weight sets used for each data stream may be specified through the use of a codebook value received from the receiver, wherein the codebook value is used to lookup preselected sets of array weights.

Similarly, the process receives data that indicates data rates for each data stream, as depicted at block **406**. By indicating the data rate for each stream, the feedback data may also be indicating an encoding scheme, and a modulation scheme. The relationship

between data rates and encoding and modulation schemes exists because different encoding and modulation schemes have different capacities. Therefore, the selection of a data rate may force the selection of particular encoding and modulation schemes.

Next, the process receives an indication of power allocation for each data stream, as illustrated at block **408**. Note that a codebook value may be used as the "indicator" that indicates data rates and power allocation for each data stream. As discussed above, a single codebook value may be used to specify an encoding scheme, a modulation scheme, and a power allocation. In some embodiments, specifying a data rate alone may specify the encoder, modulator, and power allocation. For example, if the data rate selected was zero, no power is allocated and the encoding and modulation schemes are irrelevant.

After receiving the feedback data, the process selects power settings, and encoding and modulation schemes for each data stream, as depicted at block **410**. In this step, these parameters may be selected according to a codebook value received. In alternative embodiments, some of these parameters may be calculated or derived from the feedback data received. For example, if the antenna pattern of the first data stream is indicated, the process in the transmitter may derive or calculate an antenna pattern used for the second data stream. This may be done when, for example, the second stream is constrained to be orthogonal to the first stream.

Once transmit parameters are selected as shown in block **410**, the process separates input data into data streams according to selected data rates supported by encoding and modulation schemes selected for each data stream, as depicted at block **412**. This process is implemented in data splitting function **28** shown in **FIG. 3**. As an

example, if data stream 1 operates at twice the rate of data stream 2, then two symbols are sent to data stream 1 and a single symbol is sent to data stream 2. Similarly, if one data stream has zero power allocated, all the data symbols are sent to the remaining data streams having some power allocated.

Next, the process encodes each data stream, as illustrated at block **414**. The process of encoding may be implemented with a block coder, a convolutional coder, a turbo coder, and the like.

After encoding, each data stream is modulated, as depicted at block **416**. This modulation may be implemented using a BPSK modulator, a QPSK modulator, a M-PSK modulator, a M-QUAM modulator (where M is the number of constellation points), and the like.

Following the modulating step, the process modifies the gain and phase of each modulated data stream according to respective selected array weight sets to produce data stream antenna signals for each array antenna, as illustrated at block **418**. Examples of data stream antenna signals are the outputs of phase shifters **82** in **Fig. 4**. The number of data stream antenna signals produced in this step equals the number of data streams times the number of antenna elements in the antenna array.

After producing data stream antenna signals for each array antenna, the data stream antenna signals associated with the same array antenna are summed to produce antenna signals, as depicted at block **420**. Examples of antenna signals are the outputs of summers **84** in **Fig. 4**. These antenna signals are combinations of signals from each data stream that have been weighted in gain and phase according to the selected array weight sets. This complex combination

of signals is more concisely described according to the **V** matrix used in the transmitter, which is discussed above in relation to **FIG. 1**.

Finally, the antenna signals for each antenna are transmitted, as illustrated at block **420**. The transmission step includes further processing, upconversion, and amplification needed for radio frequency transmission.

The feedback method ends, as depicted at block **424**. Although the process is shown with an end, the process may iteratively repeat in the transmitter in order to update each antenna pattern for each data stream in response to varying channel conditions.

Turning now to **FIG. 8**, there is depicted a more detailed logical flow chart that illustrates the process for estimating a composite channel and selecting array weight sets, which is shown at a higher level in **FIG. 6**. As illustrated, the process begins at block **500**, and thereafter passes to block **502** wherein the process estimates channel matrix **H** using received pilot signals, wherein a pilot signal is transmitted from each transmitter antenna. Pilots may or may not be orthogonal, but they are selected so that they are distinguishable at the receiver.

Next, the process computes a singular valve decomposition of matrix **H** to find matrix **V**, wherein $\mathbf{H} = \mathbf{US}\hat{\mathbf{V}}^{\mathrm{T}}$, as depicted at block **504**. Transmitting with this **V** matrix allows operation of the MIMO channel at near Shannon capacity for MIMO.

Thereafter, the process selects an index for a quantized **V** matrix, as illustrated at block **506**. The quantizing may be preformed by a codebook lookup, or other methods, discussed above. Note that

the quantized **V** matrix represents selected antenna array weight sets. Antenna array weight sets may be quantized as a group, or separately.

After quantizing, the process estimates a signal-to-noise ratio (SNR) of each data stream based on the transmitter using the quantized **V** matrix, and assuming equal power streams, as depicted at block **508**.

Next, the process uses the estimated SNR to determine power allocation of each data stream using a waterfilling algorithm, as illustrated at block **510**. An alternative to waterfilling is a brute-force search of all quantized possibilities. In a preferred embodiment, this parameter can be quantized to a low number of bits. For example, a reasonable choice for power allocation may be one-bit indicator for both streams "on", or only one stream "on" and the other "off".

Based on the power allocation for each stream, and the estimated SNR for each stream, the process next selects the coding method and modulation method, as depicted at block **512**. This may be implemented with a lookup that maps every SNR range to a modulator-encoder combination. In general, the coding and modulating is adapted for each data stream according to the channel quality. For example, if high channel quality is indicated by a high SNR, the modulator may be set to 16-QAM; otherwise, QPSK modulation may be selected.

Finally, the process transmits, to the transmitter, indicators for a quantized **V** matrix, a power allocation for each stream, and coding and modulation methods, as illustrated at block **514**. In a preferred embodiment, the process uses a codebook to indicate quantized antenna array weight sets, and other modulation parameters.

As depicted, the process ends at block **516**.

Referring again to **FIG. 3**, the number of antennas used by transmitter **20** is equal to the number of outputs from antenna array signal processor **58**. As shown in **FIG. 3**, antenna array signal processor **58** has two outputs, output signals **62** and **64**.

As mentioned earlier, output signals **62** and **64** may be transmitted from two antennas, or multiplexer **66** may be used to select two antennas to form an antenna array from a larger number of "available antennas", such as the four antenna elements **26** shown in antenna array **24**. Thus, in some embodiments of the present invention, there exists a set of available antenna elements, from which a subset of the "available antenna elements," from which a subset of the available antenna elements may be selected to form "an antenna array", wherein the antenna array comprises antenna elements actually used to transmit the multiple data streams.

While the embodiment in **FIG. 3** shows multiplexer **66** for selecting antennas, alternative embodiments may use the **V** matrix to select antennas mathematically by multiplying signals by zero, or non-zero values according to the matrix elements.

In order to select the antenna elements from the set of available antenna elements, receiver **98** measures a composite channel that includes all channels between all pair-wise selections of all available antenna elements and all antenna elements at the receiver. Thus, in **FIGS. 3** and **5**, between transmitter **20** with 4 available antennas and receiver **98** with 2 receive antennas, the composite channel measurement forms a composite channel matrix **H** that is four rows by two columns.

At the transmitter, there are 6 ways to choose 2 antennas from a set of 4 available antennas. The antenna array is formed with the pair that yields the highest capacity composite channel. The selection process may be described by the following expression:

$$\max_i \det\left(\mathbf{I}+\frac{1}{2\sigma^2}\mathbf{H}_i'\mathbf{H}_i\right) \tag{10}$$

where (without using waterfilling) half power is allocated to each data stream, $\sigma^2$ is the noise variance, $\mathbf{I}$ is the 2x2 identity matrix, and

$$\mathbf{H}_1=\begin{bmatrix}h_{11} & h_{12}\\ h_{21} & h_{22}\end{bmatrix},\mathbf{H}_2=\begin{bmatrix}h_{11} & h_{13}\\ h_{21} & h_{23}\end{bmatrix},\mathbf{H}_3=\begin{bmatrix}h_{11} & h_{14}\\ h_{21} & h_{24}\end{bmatrix},$$
$$\mathbf{H}_4=\begin{bmatrix}h_{12} & h_{13}\\ h_{22} & h_{23}\end{bmatrix},\mathbf{H}_5=\begin{bmatrix}h_{12} & h_{14}\\ h_{22} & h_{24}\end{bmatrix},\mathbf{H}_6=\begin{bmatrix}h_{13} & h_{14}\\ h_{23} & h_{24}\end{bmatrix}.$$

To select one of the six pairs, three feedback bits are required. In order to reduce the feedback data even more, two bits can be used to select one of four pairs.

The receiver next considers all two-by-two combinations of transmit and receive antennas, wherein there are six possible combinations of two transmit antennas and two receive antennas. For each of the six combinations, an aggregate data rate is computed, wherein the aggregate data rate is the total data rate provided by adding the data rate of data stream 1 and the data rate of data stream 2. By ranking the aggregate data rates, the antenna combination that supports the highest data rate may be selected.

In an alternative embodiment of transmitter **20**, antenna array signal processor **58** may use a **V** matrix that produces four outputs to drive four antennas in an antenna array. However, the amount of feedback data necessary to support selection of antenna array weight

sets for a four-output **V** matrix begins to consume an unacceptable percentage of capacity of the link used for feedback data. Therefore, a two-output **V** matrix is used to drive two antennas that are selected from an available set of four antennas. The two antennas that are selected support the highest aggregate data rate between transmitter **20** and receiver **98**. In the transmitter that selects antenna elements from a larger set of available antenna elements a trade-off has been made between reducing uplink feedback data and reducing downlink performance.

It should be appreciated from the discussion above that the present invention makes it possible to increase a data rate between a transmitter and receiver using a multiple-input multiple-output radio frequency channel. The feedback method disclosed is a practical solution to controlling a MIMO transceiver.

Advantages of using the MIMO radio frequency channel include the ability to double an effective data throughput without using additional communication resources, such as spreading codes, power, and bandwidth, and without employing higher order modulators. In other words, using the same communication resources, with the same modulator, the throughput can be doubled by effectively controlling the MIMO radio frequency channel. This effective control of the channel involves transmitting multiple data streams in a way that they can be separated from one another at the receiver. This MIMO channel control exploits specific knowledge of the channel gained by measuring a composite channel between the transmitter and receiver. Furthermore, proper control of the MIMO channel enables the use of linear receivers, rather than the more complex or expensive non-linear receiver. By transmitting the signal vector $\mathbf{x}$ along the channel eigenmodes (i.e., transmitting $\mathbf{z}=\mathbf{V}\mathbf{x}$ rather than $\mathbf{x}$), we can completely separate the two streams without using non-linear detectors. Thus,

with the proper control of the MIMO channel, the non-linear receiver has no substantial advantage over the linear receiver.

**Fig. 9** shows simulation results comparing quantized MIMO feedback with un-quantized, ideal MIMO feedback. There is little degradation due to quantizing.

**Fig. 10** shows simulation results for a MIMO transceiver system described above. The codebook used for this simulation is found in Table 1. The **V** matrix is selected with 5 feedback bits, and the encoding, modulation, and power allocation are selected with 4 feedback bits. The simulation results show that a MIMO system with 9 bits of feedback performs about 4 dB from the theoretical MIMO Shannon bound. Note that if some combinations of modulator, coder, and power allocation occur infrequently, they can be removed with a small loss in performance, which further reduces the feedback bits needed.

The foregoing description of a preferred embodiment of the invention has been presented for the purpose of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Obvious modifications or variations are possible in light of the above teachings. The embodiment was chosen and described to provide the best illustration of the principles of the invention and its practical application, and to enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the invention as determined by the appended claims when interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled.

## Claims

What is claimed is:

**1.** A feedback method in a multiple-stream, multiple-antenna receiver, the method comprising the steps of:

measuring a composite channel between a multiple-antenna transmitter and a multiple-antenna receiver to produce a composite channel measurement;

selecting a plurality of antenna array weight sets for use in the multiple-antenna transmitter in response to the composite channel measurement, wherein each antenna array weight set is associated with one of multiple data streams; and

transmitting information describing the plurality of antenna array weight sets for use in the multiple-antenna transmitter.

**2.** The feedback method of claim **1,** wherein the step of selecting a plurality of antenna array weight sets further includes selecting a plurality of antenna array weight sets having a cross correlation less than the inverse of a number of antenna elements in the antenna array of the multiple-antenna transmitter.

**3.** The feedback method of claim **1** further including the steps of:

selecting a data rate for each data stream in response to the composite channel measurement; and

transmitting information describing the data rate selection for use in the multiple-antenna transmitter.

**4.** The feedback method of claim **1** further including the steps of transmitting information used to describe a quality of each data stream for use in the multi-antenna transmitter.

**5.** The feedback method of claim **1** wherein the step of selecting the plurality of antenna array weight sets further includes the steps of:

selecting a first antenna array weight set from a codebook having a plurality of preselected antenna array weight sets; and

selecting a second antenna array weight set from a subset of the codebook.

**6.** The feedback method of claim **1** further including the steps of:

measuring a composite channel between a multiple-antenna transmitter and a multiple-antenna receiver to produce a composite channel measurement, wherein pilot signals are received from M number of available antennas at the multiple-antenna transmitter;

selecting N antennas to be used at the transmitter, from M number of available antennas, in response to the composite channel measurement, wherein the N selected antennas will be used to form the antenna array at the multiple-antenna transmitter.

**7.** A feedback method in a multiple-stream, multiple-antenna transmitter, the method comprising the steps of:

splitting user data to produce multiple data streams;

transmitting a pilot signal from each antenna of an antenna array;

receiving indications of a selected antenna array weight set for each of the multiple data streams, wherein each antenna array weight set includes weights associated with each antenna of the antenna array;

using the selected antenna array weight sets, weighting each data stream to produce antenna signals for each antenna in the antenna array; and

transmitting the antenna signals, wherein the multiple data streams are transmitted.

**8.** The feedback method of claim **7** further including the steps of:

encoding and modulating each of multiple data stream to produce modulated data streams; and

using the selected antenna array weight sets, weighting each modulated data stream to produce antenna signals for each antenna in the antenna array.

**9.** The feedback method of claim **7** further including the steps of:

receiving indications of a selected data rate for each data stream;

splitting data in proportion to the selected data rates for each data stream; and

transmitting multiple data streams using the selected data rates for each data stream.

**10.** The feedback method of claim **9** further including the steps of:

selecting encoding and modulation schemes for each data stream in response to the selected data rate; and

transmitting multiple data streams using the selected encoding and modulation schemes for each data stream.

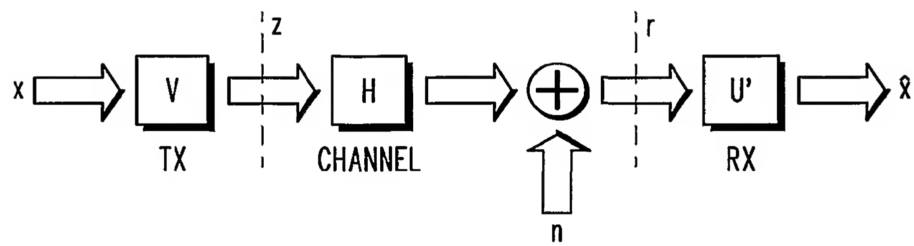

x
V
TX
z
H
CHANNEL
n
r
U'
RX
x̂

*FIG. 1*

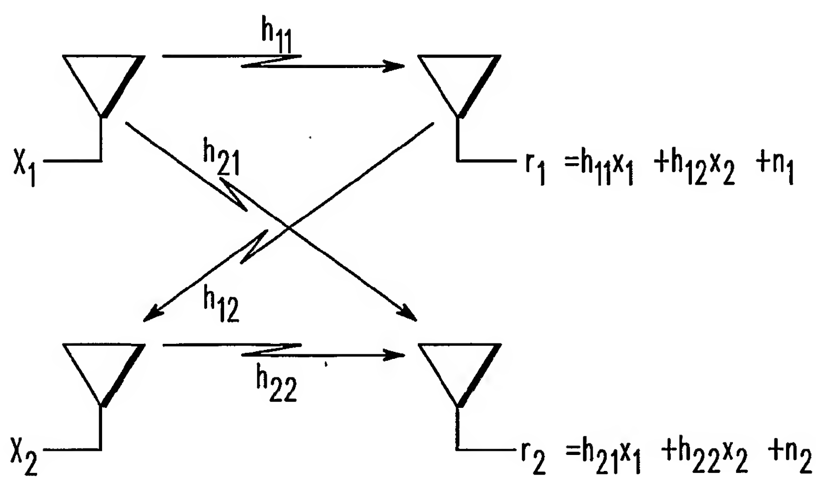

$h_{11}$
$h_{21}$
$h_{12}$
$h_{22}$
$X_1$
$X_2$
$r_1 = h_{11}x_1 + h_{12}x_2 + n_1$
$r_2 = h_{21}x_1 + h_{22}x_2 + n_2$

*FIG. 2*

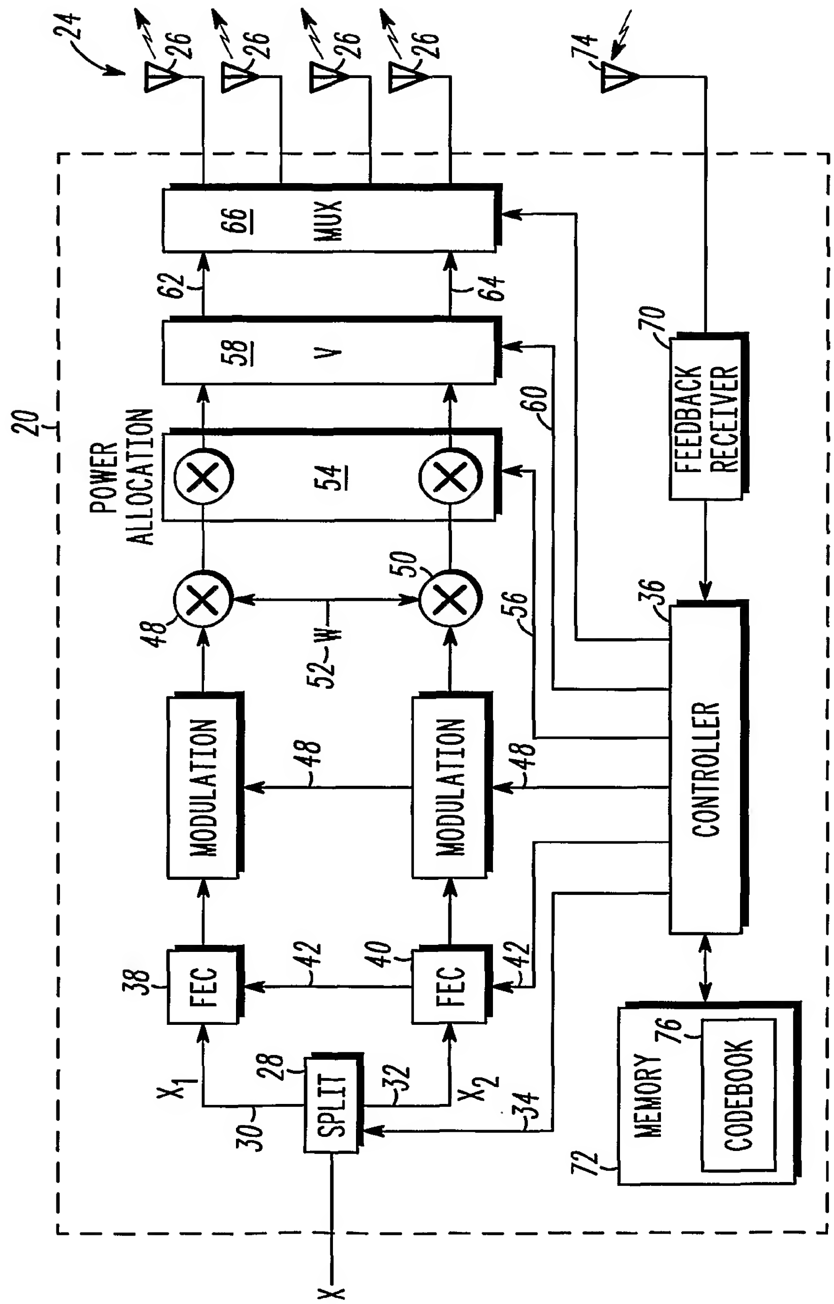

POWER ALLOCATION
MUX
V
FEEDBACK RECEIVER
CONTROLLER
MODULATION
MODULATION
FEC
FEC
SPLIT
MEMORY
CODEBOOK
X
$X_1$
$X_2$
W

FIG. 3

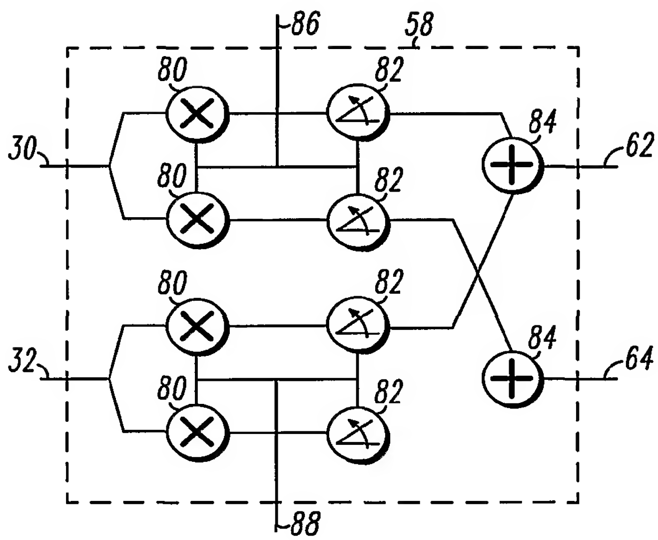



FIG. 4

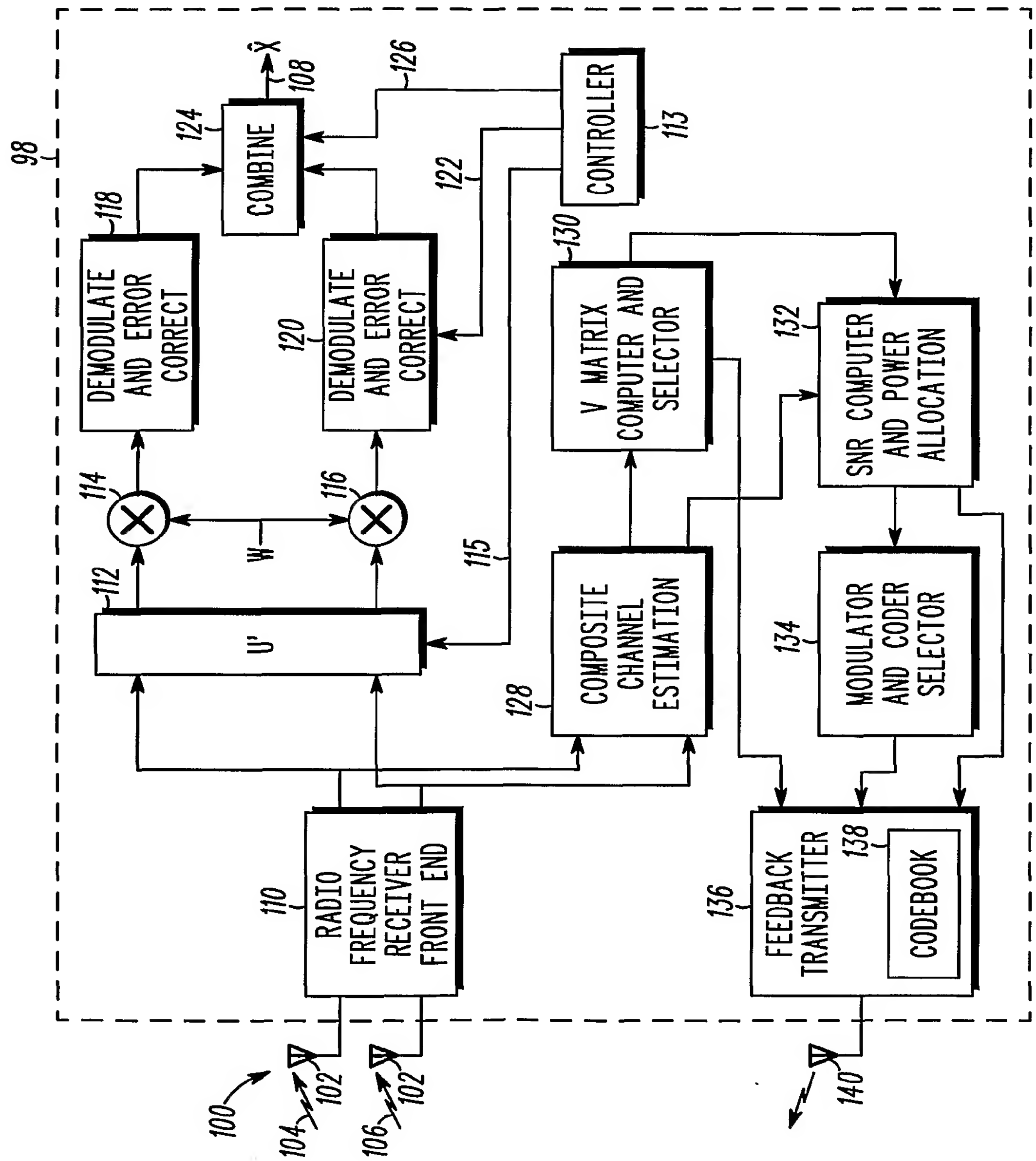
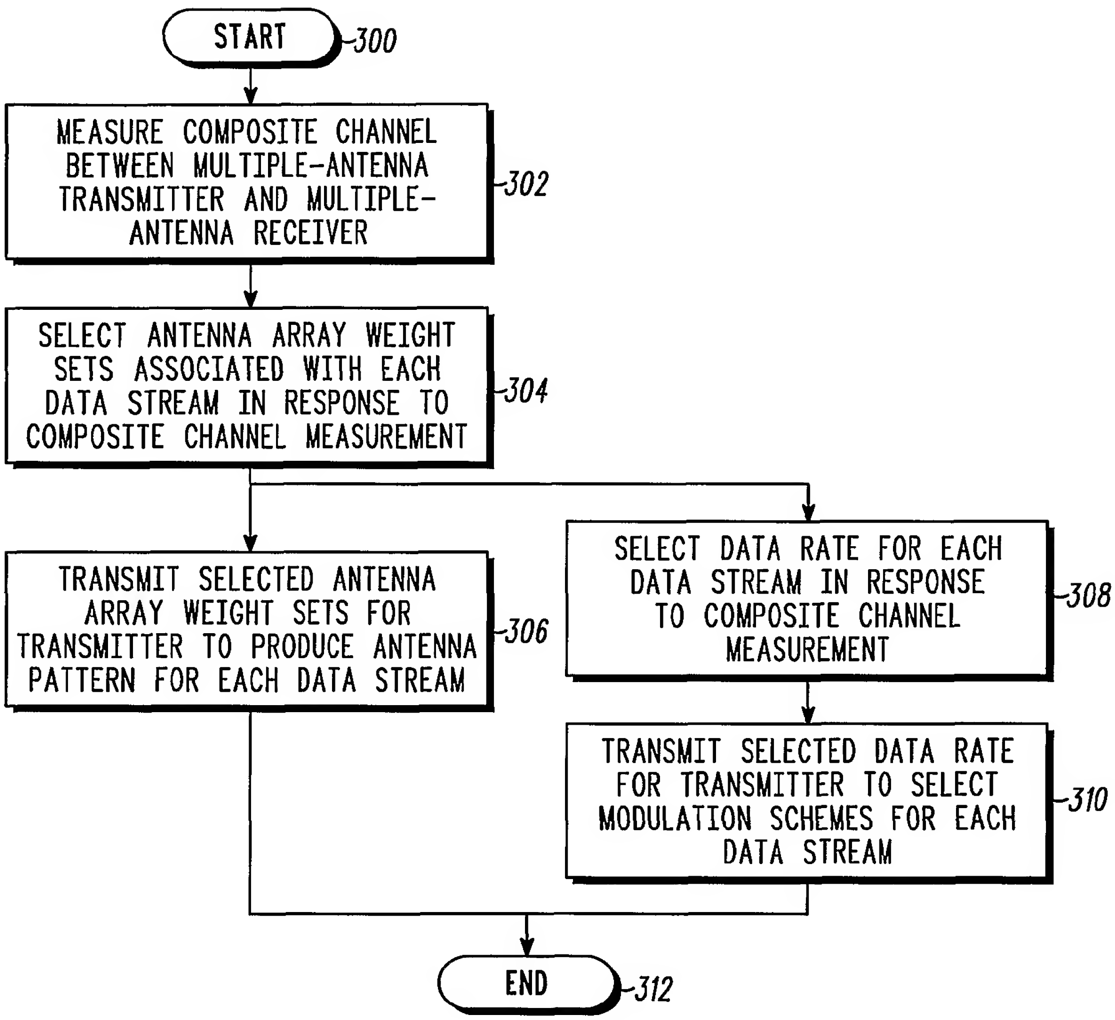

98
DEMODULATE AND ERROR CORRECT
118
COMBINE
124
X̂
108
126
CONTROLLER
113
122
DEMODULATE AND ERROR CORRECT
120
114
116
W
115
112
U'
V MATRIX COMPUTER AND SELECTOR
130
COMPOSITE CHANNEL ESTIMATION
128
SNR COMPUTER AND POWER ALLOCATION
132
MODULATOR AND CODER SELECTOR
134
RADIO FREQUENCY RECEIVER FRONT END
110
FEEDBACK TRANSMITTER
136
CODEBOOK
138
100
102
102
104
106
140

FIG. 5



START
300
MEASURE COMPOSITE CHANNEL BETWEEN MULTIPLE-ANTENNA TRANSMITTER AND MULTIPLE-ANTENNA RECEIVER
302
SELECT ANTENNA ARRAY WEIGHT SETS ASSOCIATED WITH EACH DATA STREAM IN RESPONSE TO COMPOSITE CHANNEL MEASUREMENT
304
TRANSMIT SELECTED ANTENNA ARRAY WEIGHT SETS FOR TRANSMITTER TO PRODUCE ANTENNA PATTERN FOR EACH DATA STREAM
306
SELECT DATA RATE FOR EACH DATA STREAM IN RESPONSE TO COMPOSITE CHANNEL MEASUREMENT
308
TRANSMIT SELECTED DATA RATE FOR TRANSMITTER TO SELECT MODULATION SCHEMES FOR EACH DATA STREAM
310
END
312


*FIG. 6*

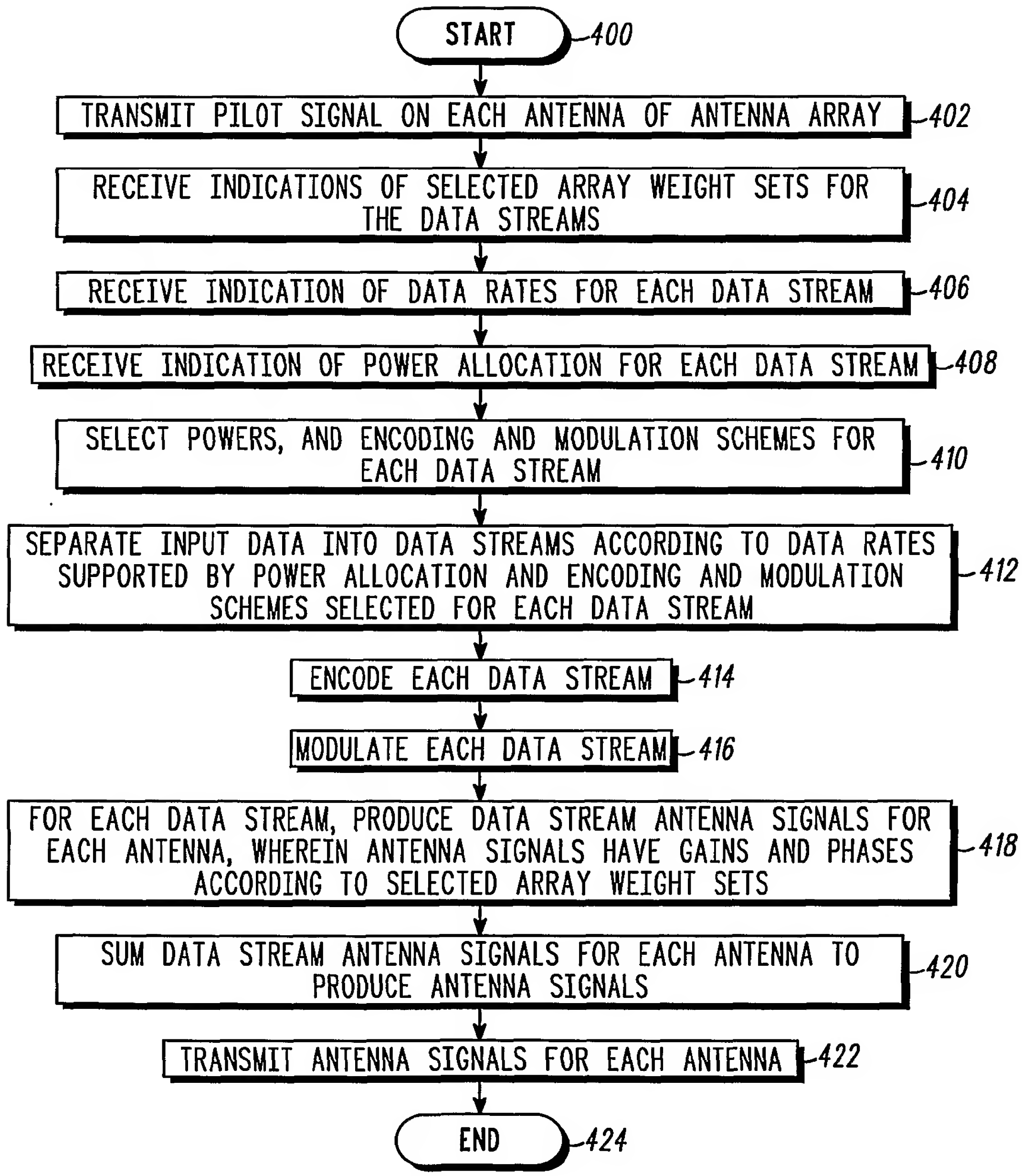

START
400
TRANSMIT PILOT SIGNAL ON EACH ANTENNA OF ANTENNA ARRAY
402
RECEIVE INDICATIONS OF SELECTED ARRAY WEIGHT SETS FOR THE DATA STREAMS
404
RECEIVE INDICATION OF DATA RATES FOR EACH DATA STREAM
406
RECEIVE INDICATION OF POWER ALLOCATION FOR EACH DATA STREAM
408
SELECT POWERS, AND ENCODING AND MODULATION SCHEMES FOR EACH DATA STREAM
410
SEPARATE INPUT DATA INTO DATA STREAMS ACCORDING TO DATA RATES SUPPORTED BY POWER ALLOCATION AND ENCODING AND MODULATION SCHEMES SELECTED FOR EACH DATA STREAM
412
ENCODE EACH DATA STREAM
414
MODULATE EACH DATA STREAM
416
FOR EACH DATA STREAM, PRODUCE DATA STREAM ANTENNA SIGNALS FOR EACH ANTENNA, WHEREIN ANTENNA SIGNALS HAVE GAINS AND PHASES ACCORDING TO SELECTED ARRAY WEIGHT SETS
418
SUM DATA STREAM ANTENNA SIGNALS FOR EACH ANTENNA TO PRODUCE ANTENNA SIGNALS
420
TRANSMIT ANTENNA SIGNALS FOR EACH ANTENNA
422
END
424

*FIG. 7*

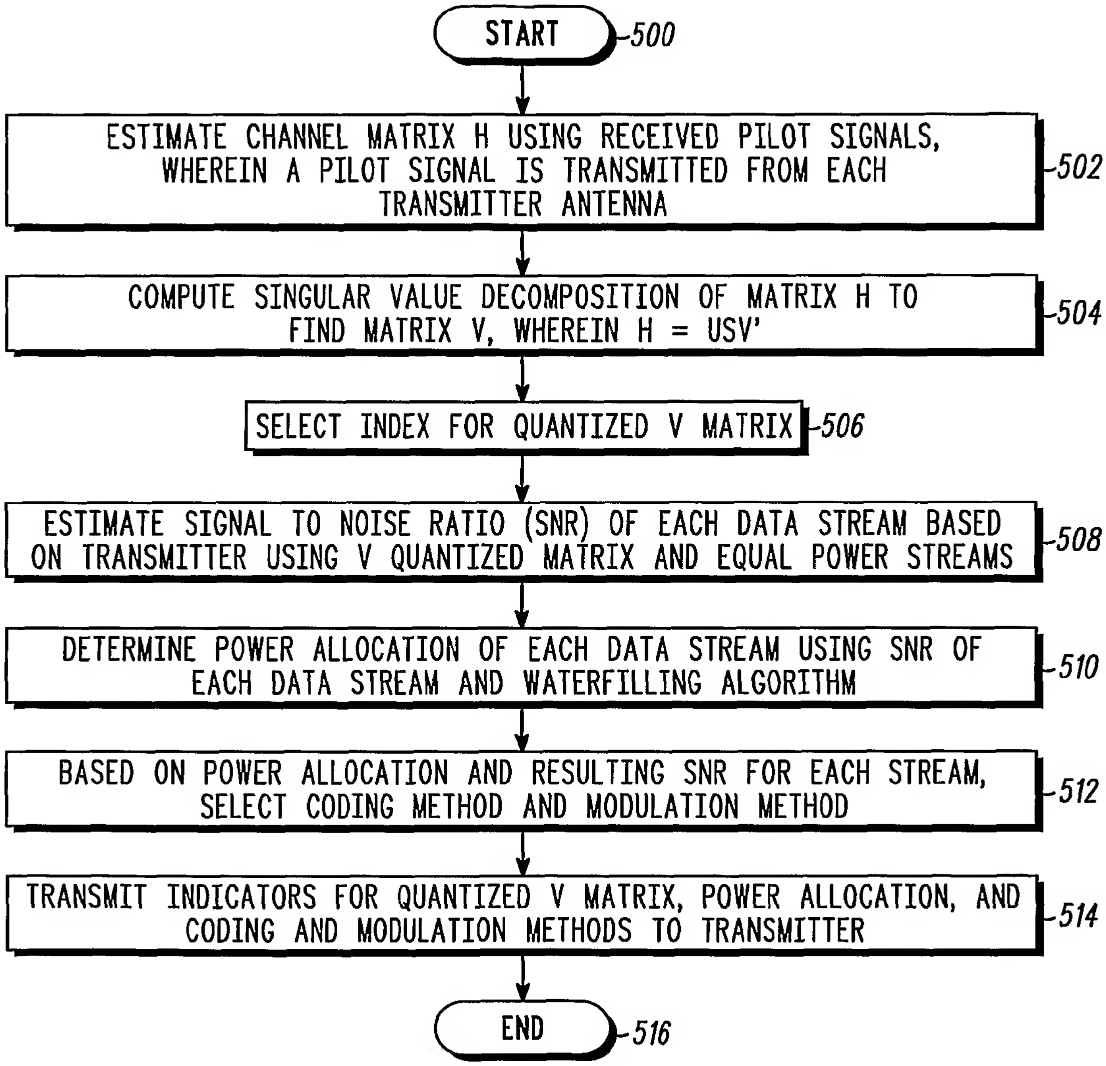
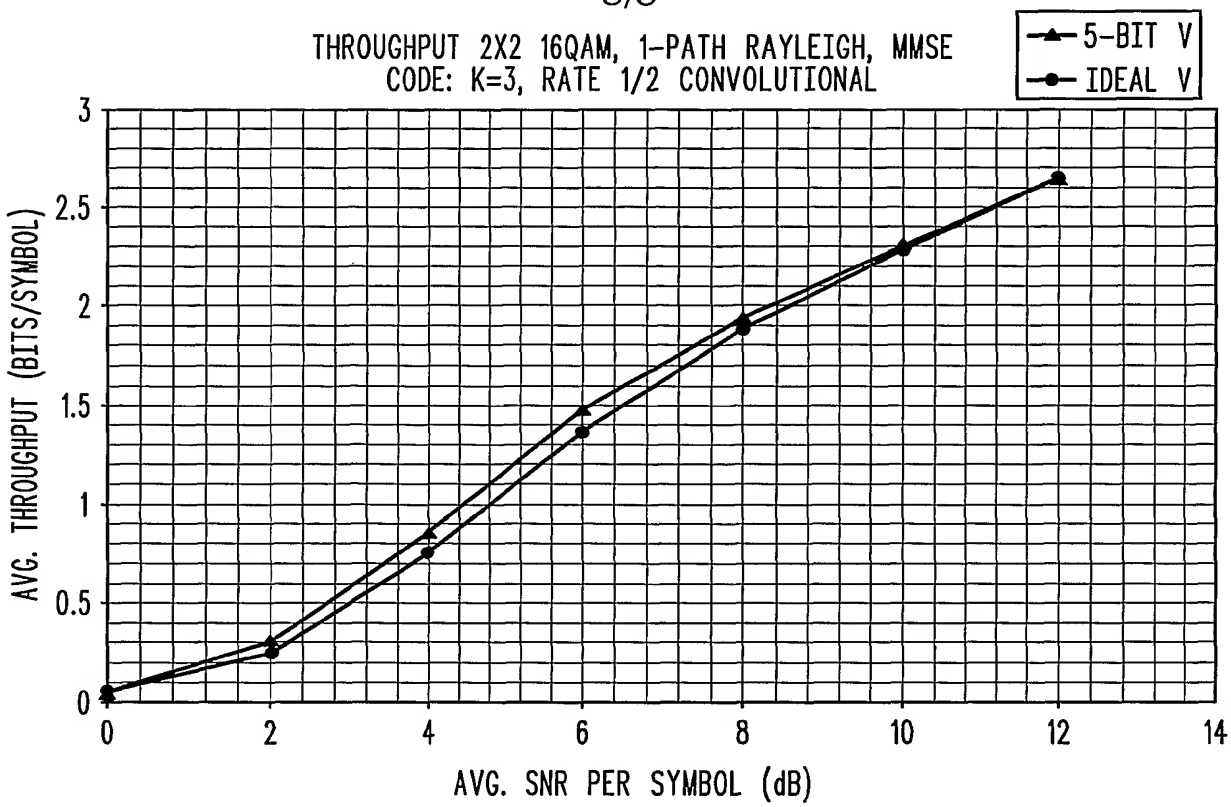

START
500
ESTIMATE CHANNEL MATRIX H USING RECEIVED PILOT SIGNALS, WHEREIN A PILOT SIGNAL IS TRANSMITTED FROM EACH TRANSMITTER ANTENNA
502
COMPUTE SINGULAR VALUE DECOMPOSITION OF MATRIX H TO FIND MATRIX V, WHEREIN H = USV'
504
SELECT INDEX FOR QUANTIZED V MATRIX
506
ESTIMATE SIGNAL TO NOISE RATIO (SNR) OF EACH DATA STREAM BASED ON TRANSMITTER USING V QUANTIZED MATRIX AND EQUAL POWER STREAMS
508
DETERMINE POWER ALLOCATION OF EACH DATA STREAM USING SNR OF EACH DATA STREAM AND WATERFILLING ALGORITHM
510
BASED ON POWER ALLOCATION AND RESULTING SNR FOR EACH STREAM, SELECT CODING METHOD AND MODULATION METHOD
512
TRANSMIT INDICATORS FOR QUANTIZED V MATRIX, POWER ALLOCATION, AND CODING AND MODULATION METHODS TO TRANSMITTER
514
END
516

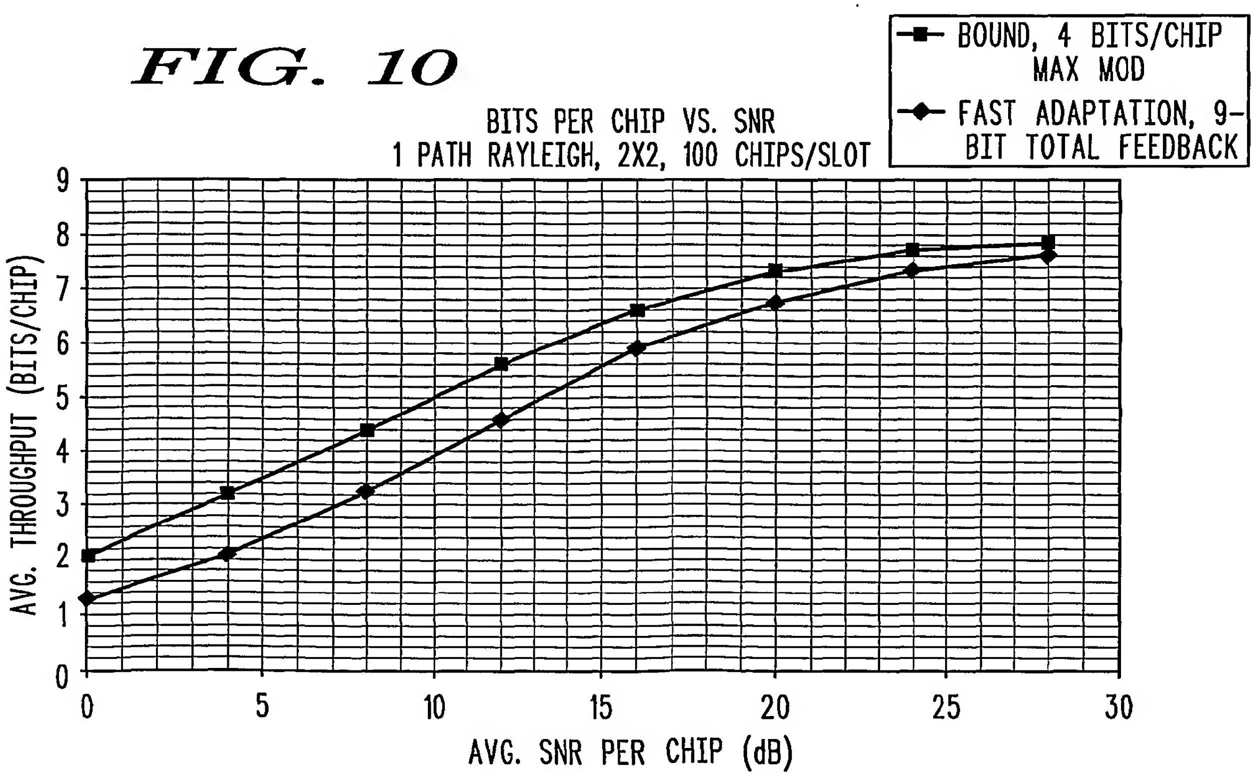
*FIG. 8*



THROUGHPUT 2X2 16QAM, 1-PATH RAYLEIGH, MMSE
CODE: K=3, RATE 1/2 CONVOLUTIONAL
5-BIT V
IDEAL V
AVG. THROUGHPUT (BITS/SYMBOL)
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
AVG. SNR PER SYMBOL (dB)


FIG. 9

FIG. 10



BITS PER CHIP VS. SNR
1 PATH RAYLEIGH, 2X2, 100 CHIPS/SLOT
BOUND, 4 BITS/CHIP MAX MOD
FAST ADAPTATION, 9-BIT TOTAL FEEDBACK
AVG. THROUGHPUT (BITS/CHIP)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
AVG. SNR PER CHIP (dB)